“Actinic-only” Defects in EUVL Mask Blanks

- Native Defects at the Detection Limit of Visible-light Inspection Tools

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ABSTRACT

We present recent experimental results from an actinic defect inspection system for extreme ultraviolet (EUV) lithography mask blanks. The current actinic inspection system has demonstrated the ability to detect 50 nm defect in cross correlation experiments with visible-light inspection tools. We found that native defects as small as 60 nm with only 3nm height were detectable by the actinic tool. These defects are just below the detection limit of current visible-light inspection tools. A new class of defect was discovered, which is quite large, in the several micrometer range, and shows suppressed non-specular EUV scattering intensity as compared to the intrinsic background scatter from the multilayer blanks. Despite their large physical dimensions, these defects are also near the detection limit of current visible-light inspection tools.

KEYWORDS: extreme ultraviolet lithography, mask, actinic, defects inspection, at-wavelength

1. INTRODUCTION

Extreme Ultraviolet Lithography (EUVL) is an extension of projection optical lithography capable of covering multiple device generations down to 30 nm[1)] using light with a wavelength range of 11-14 nm. Reflective optics are used exclusively in EUVL, utilizing special multilayer reflection coatings consisting of a periodic stack of Mo/Si bilayers. EUVL masks are also reflective. A multilayer reflection coating constructed on a robust substrate such as an Si wafer or ultra low expansion (ULE) plate forms the EUVL mask blank, and the circuit pattern is defined using a patterned absorber on top of the reflective blank.

The development of production quality masks for high volume EUVL manufacturing is a critical concern for EUVL. Defects on EUVL masks can arise either from flaws in the absorber pattern or from defects in the multilayer coating or substrate. Chrome mask-repair techniques such as selective area deposition and Ga focused ion beam (FIB) etching can be used to correct defects in the absorber layer on EUVL masks, however, there are currently no known existing technologies for repair of defects in the multilayer coating. Recent proposals of phase compensating techniques[2)] may provide a solution to this problem in the future.

Defects in or below the multilayer can either disrupt the layers, reducing the reflectivity (opaque defect or amplitude defect), or can generate a conformal multilayer topography inducing a phase error in the reflected electric field (phase defect). These opaque or phase defects on the mask blank can have a significant effect of the final aerial image.[3,4)] For the 70nm device generation, the minimum dimension of critical defects on the mask is estimated to be comparable to or even smaller than 50 nm.[5)] Phase defects consisting of pits or bumps with as little as 2 nm topography at the top surface of the multilayer are critical. [5)] The density of these critical defects must be reduced to the level approaching 0.005 defects[6)] per cm^2. Due to these very stringent requirements, the production of “defect-free” EUVL mask blanks is a major issue in the development of EUVL technology.

In support of EUVL mask blank development, defect inspection is a field of active research. Laser-based visible wavelength wafer inspection tools, which measure the optical scattering cross section of defects, are frequently used for inspection of EUVL mask blanks. These tools have the advantage of high throughput, high sensitivity, and commercial availability. Visible-light inspection tools, however, tend to have limited probing depth into the multilayer, thus, they may be inadequate for identifying all EUV printable defects, especially phase defects with very low height. Therefore, during the initial developmental stage of multilayer deposition and inspection technology, an actinic (at-wavelength) inspection is highly desirable.

Actinic inspection directly probes the effect of a defect on the reflected electric field and helps to assess the printability of the defect. An actinic inspection system may also aid in the development of a non-actinic inspection strategy and enable the use of existing inspection tools. Testing this assumption requires careful cross-correlation of EUV response of defects with respect to their visible-light scattering.

In previous publications,[7)] we reported on an actinic inspection system, referred to as an EUV scanner, based on raster scanning an EUVL mask blank under a focused EUV beam while detecting reflected and scattered radiation. We also reported cross correlation experimental results with some visible inspection tools. From these experiments,[8)] the sensitivity of the current actinic inspection tool has been determined to be as small as 50 nm in lateral size. In this paper, we present new experimental results using the actinic scanner to inspect EUV mask blanks. We report on the detection of several “actinic-only” defects that are below the detection threshold of state-of-the-art visible inspection tools.

2. At-wavelength (actinic) inspection system of EUVL mask blank defects

Briefly, our actinic defect inspection system is a raster-scanning microscope using a focused EUV beam. When a focused EUV beam is incident on a defect, the defect will induce a decrease in the intensity of the specularly reflected beam (bright field detection) and a scattering of photons into nonspecular directions (dark field detection). A conceptual schematic of the actinic inspection system is shown in Fig. 1.

The detector assembly is designed for simultaneous bright-field and dark-field detection. For dark- field detection, a microchannel plate detector is used with a hole at the center to pass the specularly reflected beam, which is captured by the photodiode bright-field detector behind the microchannel plate. The small focal spot on the sample is formed by a demagnified image of an EUV-illuminated aperture using a pair of curved, glancing angle mirrors in a Kirkpatrick-Baez (KB) configuration. The focal spot size can be changed simply by using object apertures of different sizes. The smallest spot size produced thus far is 2.5μm x 4μm when a 25μm diameter aperture is used. The EUV scanner system is installed at Beamline 11.3.2 of Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory.

The minimum detectable defect size is determined by the signal-to-noise ratio of the bright-field and dark-field channels. Defects smaller than the focal spot size can be detected by small variations of the signals. Incident beam motion relative to the fixed aperture position caused by beamline mirror heating, vibration, and synchrotron source motion creates beam intensity variation. Beam intensity variation is the largest contributor to the noise in both the bright- and dark-field signals. We have developed a feedback control system to move the aperture and track the brightest portion of the beam spot. This eliminates slow drifts in the beam intensity level on the time scale of seconds. It also suppresses noise due to motion that has a higher frequency than the loop bandwidth. Notch filters are used to eliminate certain specific vibration frequencies dominant in the noise spectrum. After this upgrade, the noise levels (1σ) are 0.1% of the bright- field signal and 1.5% of the background dark-field signal for a 4msec time constant. This is compared to levels of 0.7% in bright field and 2.5% in dark field which was established previously[7]. Through cross correlation experiments with visible-light inspection tools, we demonstrated that the EUV scanner can detect defects with sub-60nm lateral dimensions.[8] For example, we detected a 60 nm wide (FWHM) and 3 nm high multilayer-smoothed phase defect.

3. Correlation Experiment and Defect Counting Experiment

We developed two different kinds of experiments to compare results from the actinic inspection system with that of visible-light inspection tools. In the first, cross correlation experiment, a commercial visible-light inspection tool scans a low defect-density EUVL mask blank. This visible-light scan is the “pre-optical inspection” of the mask blanks. The actinic tool is then used to scan a small region in the vicinity of defects that the visible-light tool has already detected. Figure 2 shows the correlation between estimated defect sizes using a visible-light inspection tool calibrated using polystyrene latex (PSL) spheres of known size with the drop in bright-field intensity of the actinic signal. The bright-field signal is defined as the fractional reduction of the bright-field detector output relative to the neighboring clear region.

As observed in Fig. 2, the majority of defects (denoted by squares) demonstrate reasonably good correlation; these are attributed to absorbing defects on the top of the multilayer. Some defects (denoted by inverted triangles) fall significantly off the line. These defects also show off-trend characteristics in the relation of dark field vs. visible-light signal.

Investigation of the off-trend defects is performed using scanning electron microscopy (SEM) and atomic force microscopy AFM to determine their physical characteristics.

To determine the extent to which defects found by the EUV inspection tool can be found by visible-light inspection tools, we have developed a second experimental protocol. We refer to this complementary experiment as "actinic defect counting." In this experiment, the actinic tool re-scans an area that had been confirmed to be defect-free using pre-optical inspection. The mask blank is then re-inspected using a visible-light tool. This final scan is called "post-optical inspection" of the mask blanks. Defects which do not appear in the pre-optical inspection, but do appear in the actinic scan and again in the post-optical inspection are identified as "adders," namely particles that deposited on the surface during handling or in the actinic tool. Defects which do not appear in the pre-optical inspection, do appear in the actinic scan, but are not found in the post-optical inspection are identified as "actinic-only" defects. These defects are below the detection threshold of the visible-light tool used in the comparison.

4. Small Actinic-only Defects

Figure 3 shows two actinic-only defects which fell just below the sensitivity limit of a visible-light inspection tool. However, we note that these defects did register reproducible signals which were just slightly below the signal level threshold that is established using the visible-light tool. This threshold level is used to reduce the number of false counts to only one per wafer.

From the cross correlation results with the PSL-calibrated visible-light inspection tool, we can estimate the size of a defect based on the actinic bright- and dark-field signals. For the defect shown in Figs. 3(a) and 3(b), the estimate of defect size is 52 nm, as determined from the bright-field signal intensity of 0.15%, and 81 nm, as determined from the dark-field signal intensity of 27%. Grayscale images for the bright- and dark-field signals have opposite contrast because the bright field detects small decreases of reflected intensity while the dark field detects small increases of scattered intensity. The size of the defect shown in Fig. 3(a) and (b) as estimated from both the bright- and dark-field intensities are almost the same. We therefore identify this defect to be an absorbing defect on the top of the multilayer.

The small defect depicted in Figs. 3(c) and 3(d) is identified a phase defect. There is no noticeable change in the bright field intensity (Fig. 3c), and a 12% increase of scattered intensity relative to the multilayer blank region in the dark field (Fig. 3d). AFM analysis showed a topography on top of the multilayer coating of 3 nm height and 60 nm wide (FWHM).

5. A New Type of Defect

During the cross correlation and defect counting experiments, we found a new class of defect showing abnormal dark-field characteristics. Figure 4 shows bright- and dark-field images of such a defect, as well as an SEM image. Since this defect is larger than our beam spot size, we can measure the size directly from the image. The size in both the bright- and dark-field images was 35 μm, which is consistent with the SEM image. This defect induced a 94% decrease in the bright-field intensity, i.e. most of the incident beam was absorbed by this defect. Interestingly, the dark field showed a 52% decrease. Typically, we find that large defects exhibit a significant increase in the dark field scattering signal. A size estimate based on pre-scan data from the visible-light inspection tool was only 178 nm, and energy dispersive spectroscopy (EDS) data showed this defect to have organic components. The small particles in the dark-field image showed the increased scattering signal as a more typical defect would.

When the actinic tool scanned this area again, however, the small particles had disappeared. Given this, we postulate that the estimated size of 178 nm based on pre-optical inspection corresponded to one of these particles and that the first actinic scan vaporized these small organic particles. We have observed this type of defect twice again from two different samples. We are still investigating the characteristics and origin of these defects.

6. SUMMARY

Using an actinic defect inspection tool, we have found several defects on EUVL mask blanks that are below the detection threshold of present state-of-the-art visible-light defect inspection tools. However, only slight improvement in the detection sensitivity of the visible tools appears to be required for these defects to be reliably detected. Based on the preliminary results, we have considered that visible-light tools will ultimately be able to detect all printable defects on EUVL mask blanks such that an actinic tool will not be required to support production requirements. However, much more research of the type reported here will be required in order to develop a statistically significant amount of data upon which to base such a decision.

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Figure Captions

Fig. 1 Schematic diagram of actinic EUVL mask inspection system. Two graphs on right-hand side show the typical line scans of bright and dark fields through a defect. Upper scan is the bright field showing 0.3% drop of specularly reflected beam intensity. The lower scan is the dark field showing about 40% increase of non-specularly scattered beam intensity.

Fig. 2 Relationship between bright-field (BF) signal intensities and estimated defect sizes using a visible-light inspection tool calibrated using PSL spheres. The off-trend defects are identified by inverted triangles.

Fig. 3 Images of small actinic-only defects found in the correlation experiments with visible-light inspection tools. (a) Bright field image of an amplitude defect showing 0.15% drop of reflected intensity. (b) Dark field image of an amplitude defect showing 27% increase of non-specularly scattered intensity than multilayer blank. (c) Bright field image of a phase defect (3nm high and 60nm wide) showing no evidence of detection. (d) Dark field image of a phase defect showing 12% increase of non-specularly scattered intensity than multilayer blank.

Fig. 4 Images from a defect showing strange dark field scattering (non-specular scattering from this defect is less than the background scattering from multilayer blank). (a) Bright field image showing 94% drop of reflected intensity. (b) Dark field image showing 52% drop of non-specularly scattered intensity than multilayer blank and also some debris showing the increased non-specular scattering are observed. (c) SEM image of this defect.

REFERENCES

[1] C. W. Gwyn, R. Stulen, D. Sweeney, and D. Attwood, J. Vac. Sci. Technol. B 16(6), 3142 (1998).

[2] A. K. Ray-Chaudhuri, G. Cardinale, A. Fisher, P. –Y. Yan, and D. W. Sweeney, J. Vac. Sci. Technol. B 17(6), 3024 (1999).

[3] Y. Lin, and J. Bokor, "Minimum critical defects in extreme-ultraviolet lithography masks", J. Vac. Sci. Technol. B **15**(6), 2467-2470, Nov/Dec 1997.

[4] K. Nguyen, PhD dissertation, University of California, Berkeley, 1994.

[5] E. M. Gullikson, C. Cerjan, D. G. Stearns, P. B. Mirkarima and D. W. Sweeney, J. Vac. Sci. Technol. B 19(6), (2001).

[6] S. Hector and P. Mangat, J. Vac. Sci. Technol. B 19(6), (2001).

[7] S. Jeong, M. Idir, Y. Lin, L. Johnson, S. Rekawa, M. Jones, P. Denham, P. Batson, R. Levesque, P. Kearney, P. Yan, E. Gullikson, J. H. Underwood, J. Bokor, "At-wavelength detection of extreme ultraviolet lithography mask blank defects", J. Vac. Sci. Technol. B, **16**(6), 3430-3434, Nov-Dec, 1998.

[8] M. Yi, T. Haga, C. Walton and J. Bokor, J. Vac. Sci. Technol. B, **19**(6), Nov-Dec, 2001.